

Properties of coatings on sintered iron alloys

M. Rosso*

Materials Science and Chemical Engineering Department – Polytechnic of Torino
C.so Duca degli Abruzzi, 24 10129 Torino, Italy

* Corresponding author: E-mail address: mario.rosso@polito.it

Received in revised form 15.07.2006; accepted in final form 30.10.2006

Properties

ABSTRACT

Purpose: In this paper the attention has been focused on the thermal spray coatings applied to PM steels, in particular the studies have been directed to unalloyed and to molybdenum alloyed sintered samples, coated with WC-Co and WC-CoCr powders, using the HVOF process.

Design/methodology/approach: The performance of HVOF coatings on sintered steels were studied after spraying the samples with WC-Co and WC-CoCr powders. The porosity of the specimens allows enough adhesion between substrate and coating, in this manner previous grit blasting of the surfaces of substrates are not necessary.

Findings: Regarding the properties of coating layers the composition of the substrate has no remarkable influence, being the sprayed powders composition and the process parameters the most influencing factors. The two powders shown in the as-sprayed state decomposition of the tungsten carbide and an amorphous metal binder. The WC-Co coatings contain more tungsten oxidation products compared to WC-CoCr coatings. Chromium might have a function as an oxidation buffer: in oxygenating atmospheres it partly protects tungsten carbide from oxidation by forming Cr_2O_3 .

Research implications: Adhesion of the coatings was the weak point of coatings originated from the WC-Co powder, whereas the cohesion was sometimes insufficient within the WC-CoCr coatings.

Practical implications: The wear mechanisms, which occurred during sliding friction, are similar for the different coatings: after a run-in phase, in which the asperities are mainly abrasively worn away, adhesive and abrasive processes take place. Chromium seems to increase the carbide binding function of the metal matrix and to reduce the residual stresses within the coating.

Originality/value: The overall performance of the WC-CoCr coatings is the best, the supreme quality of WC-CoCr coatings being the reduced tensile stresses and the good bonding strength. All these properties relate to the presence of Cr within the metal matrix, it partly prevents WC from oxidation, it increases the hardness via solid solution hardening and by forming Cr_2O_3 , what also increases the corrosion resistance of the coating, and it binds tungsten carbide in an excellent way.

Keywords: Wear resistance; Sintered steels; WC-Co and WC-CoCr coatings; Thermal spray coatings; HVOF spraying

1. Introduction

The optimal performance of a component is to a great extent determined by the state of the surface, because every workpiece is exposed to several strains, namely mechanical, thermal, chemical or electro-chemical, radiation stresses, which often have their maximum in the surface area. Owing to the presence of this

complex strain most failures of machine components start within or close to the surface.

The high importance of the surface in regard to the lifetime of a component justifies the term “surface engineering”, which combines the knowledge of different scientific disciplines and deals with the design of a composite system which has properties, that cannot be achieved by either the surface layer or the bulk component alone [1].

Surface engineering can be seen as one of the key technologies of the present days, permitting to lengthen the lifetime of the products, simultaneously reducing costs and saving natural resources. The surface of a component can be changed through a various amount of surface treatments. In particular the surface treatments of metals can be based on metallurgical changes and/or chemical reactions within a controlled environment such as a specific temperature-time-function or a defined atmosphere, that is thermal and thermo-chemical surface treatments, like surface hardening, nitriding, nitrocarburising, carburising, boronising, manganising. Mechanical operations classified as finishing can also constitute suitable surface treatments.

Besides the previous surface treatments, several coating treatments can be applied to improve the properties of a surface, these add at least one layer to coat the original work-piece. Through coating the surface of a workpiece, one gains a coating-substrate composite system. So the different functions of a component are carried out by different layers: the substrate, the substrate-coating interface and the coating layer. Each solving proper functions, the purpose of a coating being generally related to wear resistance, protection against corrosion, thermal and electrical insulation, optical appearance of the work-piece. The substrate-coating interface is important for adhesion and diffusion barrier, while the substrate can guarantee strength, stiffness and weight.

One layer or more can be added as coating, depending on the way of production of the coating there are coatings where the deposited material prior to deposition is in a gaseous phase, e.g. ion implantation, CVD and PVD processes, or in a liquid phase, e.g. electro-deposition, sol-gel processing, or in a molten or semi-fuse phase methods, that is all the thermal spraying techniques. As for the PVD coatings, they have shown their potentialities especially in the field of PM tool steels [2].

Several aspects have to be considered when choosing a surface treatment, owing to its possible interference with important properties of the bulk material, regarding the use of the work-piece the bulk surface system as a whole must have better properties than the work-piece without the surface treatment. Moreover, the surface process must also be adequate regarding the geometry of the component, this can lead to either redesigning the work-piece or changing the process. Also the cost-effectiveness of the surface process plays an important role, every process makes use of energy and limited natural resources. At the same time, improving the lifetime of the work-piece, resources can be saved.

Thermal spraying processes [3] are able to produce a large assortment of protective coatings, because almost every material can be used for coating and there is a wide substrate range. It is also possible to change the coating materials or/and the process parameters, so that one can achieve a multi-layer or a graded coating.

The advantages of a chosen bulk-surface system can be related to reduced production costs, failure of the part without damaging the whole machine or even risking human lives, possibility of local repair of damaged machine parts, minimal variation of the original design, energy and resource saving as well as environmental protection.

In this contest the perspective of the coating industry is a very good one. Besides the combination of new or known processes, coating engineering gains interest towards multi-layer coating.

The internal layer is responsible for a good adhesion to the substrate, there is a gradually change of the properties with each additional layer so that the outer layers have the optimal properties to fulfil the functions they are designated for.

The use of computers, through knowledge-based systems, which can be updated very easily, can assist a surface engineer to find the optimal solution to surface problems also taking economical and ecological viewpoints into account, moreover automation of surfacing processes is also possible with the help of computers, so surfacing can be a part of a normal production line.

Thermal spray processes may be useful tools for forming PM parts [3, 4], too. Moreover, they can meet interesting applications to coat PM components, especially in applications where elevated surface hardness and wear resistance combined with high toughness characteristics are required. In fact, the demand of structural parts with improved properties is higher and higher, in the automotive industry field especially, in this contest PM alloyed steels meet with extensive applications and can replace parts produced by conventional manufacturing processes, such as casting or forging. The need for the increase of the performances of many components requires the execution of proper heat treatments and the increasing utilisation of sintered materials for mechanical components is due to the possibility to carry out thermal and thermochemical treatments, like boronising, carburising, nitrocarburising, nitriding, as well as induction hardening, even if many times the porosity of the parts constitutes a problem and limits the choice of the process or requires additional treatments [4,7]. In this contest, thermal spray techniques may represent effectively a good economic solution, because a porous surface may constitute an optimal base for the application without the requirement of additional operations for surface roughening and preparation. In this case the porosity, more than a drawback, acts as a coupling tool, providing the adhesion between substrate and coating layer. Moreover, unlike thermal and thermochemical treatments, coatings may be applied to parts having reduced density or produced with unalloyed powders, with important savings in powders, energy and production costs.

The research regarding the application of the spray processes has been developed in other directions too. In particular, very important results have been obtained applying HVOF, as well as plasma coatings based on ceramic and WC-Co materials to dies and tooling used for diecasting processes. The applied coatings combat the heat checking and contribute to improve the thermal fatigue life [8,9]. Further field of application of HVOF and plasma spray coatings has been focused on the enancement of erosion resistance of components and parts to be applied in the water treatment equipments and implants, as well as to other industrial components, using different type of powders and processes [10 - 15].

2. Experimental part

Different sintered iron alloys, Fe-Cu, Distaloy AE, Astaloy Mo, were considered and series of test pieces were compacted and sintered. Two types of specimens were produced, the first one to be used for the wear tests were disk shaped, with a diameter of 40 mm and 10 mm thick, while the second one to be used for adhesion and cohesion tests had cylindrical shape, measuring 27 mm in height and 24.9 mm as diameter. Borings were drilled on all the samples, without deteriorating their surface, on the disk

shaped with a diameter of 16 mm, centred within small tolerances, while on the cylinders the borings were for mounting the test pieces to the adhesion and cohesion test machine. The chemical composition and the sintered density of the specimens are in table I, the iron-copper samples (type A) are based on the Fe powder ASC 100.29, while type B samples were sintered from Distaloy AE powder and type C from pre-alloyed Astaloy Mo powder.

The sintered and bored specimens were coated by HVOF spraying two different powders based on tungsten carbide: the first one with Co (17 wt %), while the second one contained 10 wt % Co and 4 wt % Cr, balance being WC, the spherical shaped particles having a size distribution mainly in the range 15 to 45 μm . Two different set of processing parameters were adopted, the first one, indicated with number one, was referred to standard parameters, it means with neutral atmosphere, while the second one, indicated with number 2, was characterised by two steps: an initial step with reducing atmosphere due to reduced oxygen content, followed by a final step with standard parameters. The final coating thickness was for the whole samples about 380 μm .

The disks for the wear test were mounted on a torque motor and coated along their circumferences, while the cylinders for the adhesion and cohesion tests were coated on their frontal surfaces, where no boring was drilled, pairs of samples at least were coated for each condition.

The wear behaviour of the coatings was examined performing disk-on-disk wear tests, employing an AMSLER machine, with relative sliding of two disks and applying a load of 700 N, no lubricant was used achieving dry friction. The wear tests were performed with two disks each coated with the same parameters. Their initial masses and diameters were measured, repeating the measures at relative sliding distance of 250, 2500 and 6500 m. The disks having the same diameter, the sliding was obtained by different angular speeds between upper and lower disks. During the tests and due to the wear, the sliding velocities decreased from 0.869 m/s to 0.862 m/s for the lower disk and from 0.790 m/s to 0.783 m/s for the upper one. The relative tangential speed, at which the lower disk moved faster than the upper one, was constant at each moment and measured 0.079 m/s. Two pairs of not coated disks each type of sintered steels were also mounted and tested on the AMSLER machine.

The frictional torque was also read at the same distances, together with surface analysis of disks to measure the texture parameters by means of a profile meter, provided by a diamond stylus with a tip radius of $2\ \mu\text{m} \pm 0.5\ \mu\text{m}$ and having a resolution of 32 nm.

On the cylindrical samples the adhesion and cohesion test was performed with relation to the Standard ASTM C 633. The frontal part of two test specimens HVOF sprayed using the same parameters were both coated with a specific bonding agent. Then the whole test assembly was mounted on the tensile test machine (MTS system) and tensile load was applied at a constant rate until rupture occurred.

The micro-hardness of the test pieces was measured by Vickers indentation from the cross-section of the coatings and substrates on the cylinders with a load of 29.4 N, while the hardness of the coatings was measured as surface Rockwell (R 15N), applying to the cone shaped diamond a load of 15 kg.

Structural information was achieved by X-rays diffraction analysis performed on the original powders and on a sample of each coating.

The morphology of the coatings was observed by light optical microscopy on the cross section of different coatings in the as-sprayed state and after etching with Murakami's reagent. Finally, SEM was performed on the sintered bulk materials and on the coated disks in the as-sprayed state and after the wear test.

3. Results

The X rays diffraction patterns of the WC-Co powder indicate the presence of only Co and of WC, whereas the WC-CoCr powder, beside WC and Co, also contains W_2C and the composite cobalt-tungsten carbide $\text{Co}_3\text{W}_3\text{C}$. Comparing the diffraction patterns of the original powders with those of the sprayed coatings, it appears that decomposition of WC, to W_2C and W, has taken place, the degree of decomposition depending on the powder and, to a small extent, on the spraying parameters. Spraying using non standard parameters reduces the amount of the decomposition of tungsten carbide. The diffraction patterns of WC-CoCr coatings do not reveal the presence of metallic tungsten and also the presence of W_2C appears in reduced amount.

The macro-hardness of all coatings do not vary significantly, their values being about 91 HR 15 N. The micro-hardness profiles show light differences as a function of coating materials and parameters, when standard parameters were adopted the micro-hardness of the layers maintain constant values, with sharp fall at the interface up to the micro-hardness values proper of the substrate. The mean micro-hardness of the WC-Co/1 coatings is about 1045 HV0.3, while for the WC-CoCr/1 coatings the mean value was 1100 HV0.3. The micro-hardness profiles of coatings and of type B substrate close to the interface are shown in figure 1. The micro-hardness characteristics of the substrates depend upon their chemical composition and density, being about 100, 160 and 220 HV0.3 for types A, B and C respectively.

The average weight losses of the coated disks are dependent upon the coating layer characteristics, as derived from the powder composition and from the spraying parameters, and no influence of the substrate was observed. A comparison with the behaviour of the as sintered disks is impossible, because there was very strong wear and their surfaces were roughened due to deposited debris and the tests were interrupted after 500 m only. The wear was more strong on the lower disks, because they moved faster than the upper ones and allowed to better differentiate the coated disks, the differences being essentially related to the first 2500 m of sliding, where the WC-Co coatings appeared the most resisting, while all other coatings shown higher wear rate even if of similar magnitude. After the sliding distance of 2500 m wear rates decreased to similar values and the surfaces became smoother (figure 2).

The coefficient of sliding friction was about 0.2 when starting the tests and increased at about $0.6 \div 0.65$ after the first 10 m of sliding distance, reaching a quite stable value in the range of about 0.5 successively the 100 m of sliding, without significant differences between the different coating materials.

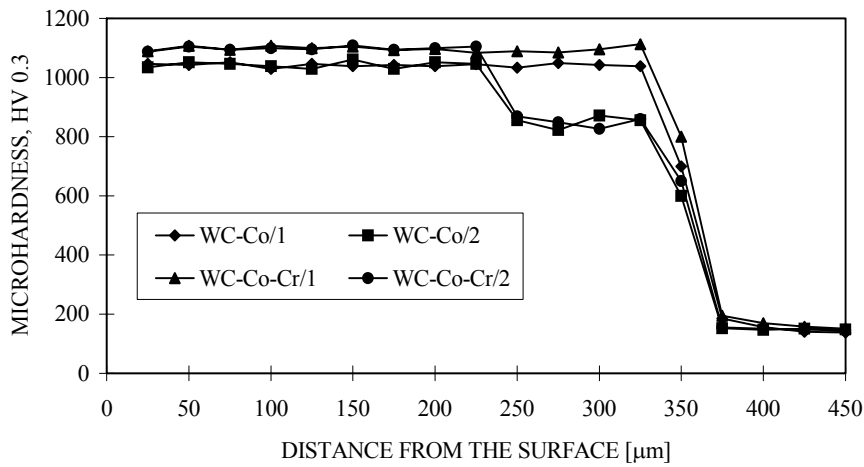


Fig. 1. Microhardness profiles of coatings and of substrate close to the interface of type B substrate

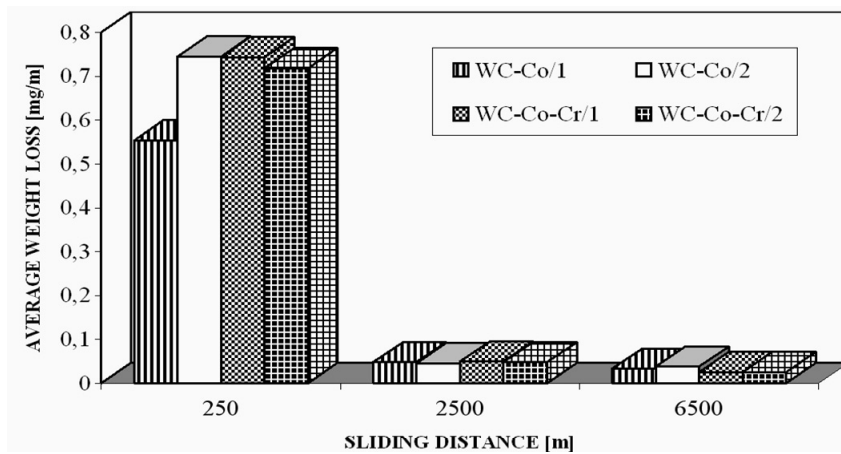


Fig. 2. Average weight loss of coatings on the upper disks as a function of sliding distance

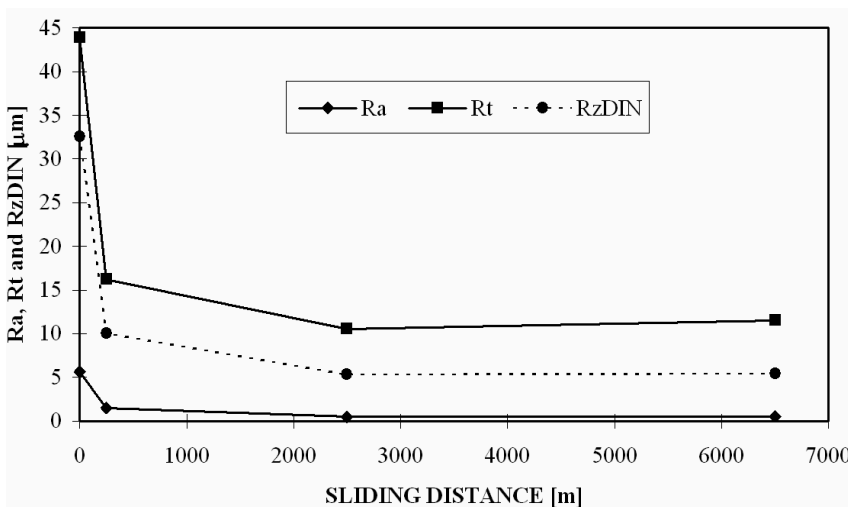


Fig. 3. Average R_a , R_t and R_{zDIN} roughness values of the coatings of upper disks as a function of sliding distance

Table 1.
Chemical composition (wt %) and density [Mg/m^3] of sintered samples

Sample	C	Cu	Ni	Mo	S	Fe	Density
A	0.16	1.0	-	-	0.002	Bal.	6.8
B	0.2	1.5	3.95	0.5	0.02	“	6.9
C	0.1	-	-	1.5	0.007	“	6.9

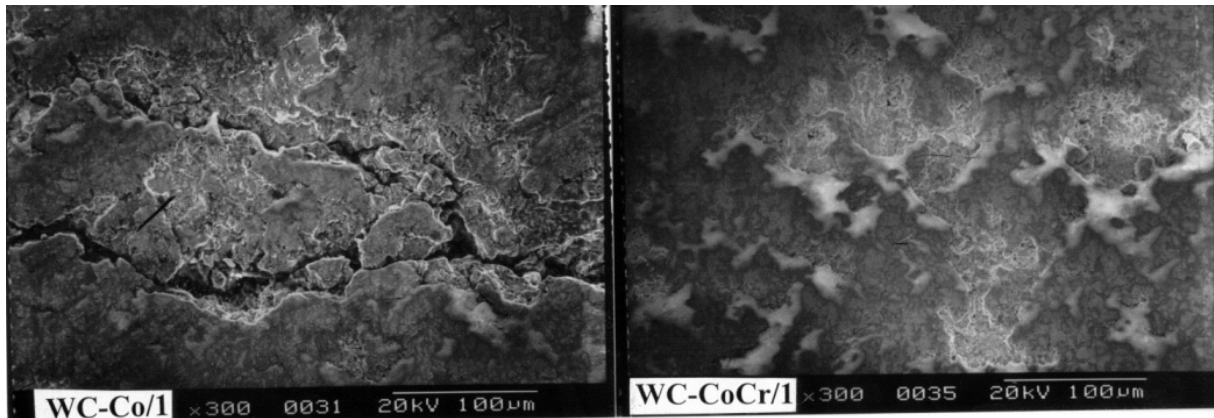


Fig. 4. Morphology of WC-Co/1 and WC-Co/2 coatings and SEM microphotographs of WC-Co/1 and of WC-Co-Cr/1 coating layers surface

The texture of the original surfaces and the changes of the parameters of the texture of the coatings during wear were also examined and in the diagrams of figure 3 the main parameters are represented, that is:

- R_a , the average peak-to-valley height, which is the arithmetic mean of the departures of the profile from the mean line
- R_t , the maximum peak-to-valley height within the assessment length
- R_{zDIN} , the mean of the R_t values, obtained for each sampling length within the evaluation length

The coated layers show quite high roughness values, however the run-in strongly reduces the surface asperities and all the parameters drop at quite low and constant values.

About the adhesion and cohesion tests, all the WC-Co coatings sprayed with standard parameters the bonding agent failed prior to the coatings, while the WC-Co coated with non standard parameters failed at the substrate-coating interface at considerably low strength values, ≈ 13 MPa. All the WC-CoCr coatings failed within the WC-CoCr layers, with higher loads in the case of standard parameters sprayed coatings, >14 MPa.

The microstructure of the coatings appeared essentially of the amorphous type, the sequences of splats being observed, moreover the layers sprayed with non standard parameters seemed more porous.

The SEM observation of the surface of coated disks, figure 4, highlighted the presence of cracks, having the main orientation normal to the circumference, on the WC-Co coatings. It was recognised that the non standard sprayed coatings shown a higher crack intensity, however on the WC-CoCr coatings never was observed the presence of cracks.

4. Discussion

The X-rays diffraction patterns show that tungsten carbide during spraying process is decarbonized to W_2C or even metallic tungsten, the amount of decomposition being influenced by the spraying parameters and by the powder composition. In fact the reducing atmosphere obtained when using the non standard parameters tends to decrease the amount of oxidation and consequent decomposition of tungsten carbide. Moreover, the presence of Cr in the sprayed powders seems to protect the tungsten carbide from decarburising, that is chromium might have the function of an “oxidation buffer”. In neutral atmospheres, it partly protects tungsten carbide from being oxygenated by forming chromium oxide, whereas in reducing atmospheres it does not react with oxygen to the same extent, what would explain that the decrease of the amount of transformed tungsten carbides is not as strong as it is in the absence of chromium.

The X rays diffraction did not detect residual tensile stress, which would cause the peaks to shift towards higher angles within the diffraction pattern.

It can be seen that the coating, which contains chromium, has an increased micro-hardness. Because occurred transformations of tungsten carbide do not influence the micro-hardness of the coating, it depends on the specific carbide-metal system and the porosity of its coating, which is influenced by the porosity of the original powder and by the spraying parameters such as temperature and particle velocity. Besides the possibility, that the porosity of the WC-Co coating differs from the one of WC-CoCr coatings, and the slightly higher WC content of these ones the chromium could also be responsible for the highest micro-hardness values. Addition of chromium to the powder affects the

micro-hardness in different ways. Cr, when it is dispersed into the cobalt matrix, causes the formation of mixed crystals. These mixed crystals within the metal matrix of the coating cause solid solution hardening, what increases the micro-hardness of the coating. Another effect, which increases the micro-hardness of the Cr alloyed coating, is the oxidation of chromium to Cr_2O_3 .

The coatings sprayed with non standard parameters, have lower micro-hardness on the portions of the coatings, which were sprayed with reduced oxygen content. In fact it is known that spraying with standard parameters and, thus, under neutral atmosphere, results into lowest porosity. If the atmosphere is a reducing one, the porosity of the coating increases strongly, because the velocity of the spraying particles is reduced and they do not form a compact layer. The stronger decrease of micro-hardness of the portion of the coating, which was sprayed with the Cr containing powder under changed parameters, compared with the change of the WC-Co coatings, may be the result of both an increased porosity to a greater extent compared to the cobalt containing powder, and a lower content of chromium oxide, probably the second one will be predominant.

The possibility of a continuous measurement of the coefficient of sliding friction shows that during the first 100 m the coefficient goes through several changes and it has gained considerable stability after this distance. Then the initial sliding distance of 100 m corresponds to the phase of the run-in period. The coefficients of sliding friction increase very strong in the first 5 m to 10 m. This steep increase can be caused by the dominance of abrasive wear: the asperities of the unworn surfaces contact each other and cause each other to be worn away, however during this mostly abrasive phase, adhesive processes play a role, too. The abrasion of the asperities increases the contact area, what would give rise to the coefficient of sliding friction. After 15 to 30 m, the sliding friction starts to decrease, until it reaches the level, at which it remains - more or less - constant for the rest of the sliding distance. This reduction of the sliding friction might be caused by the smoothing of the surface. Also wear debris might help to reduce sliding friction by rolling between the two surfaces. After 100 m, however, the sliding friction is stable. This could indicate, that the surface has changed from the original shape to the profile, which is shaped similar the one of 250 m. Also the wear mechanisms, which were present so far, will continue further: the adhesive and the abrasive wear.

Even if the coefficients of sliding friction remain constant after 100 m, the coatings and their average wear rate show important change between 2500 m and 6500 m of sliding distance (Figure 2). Therefore the phase after the run-in period is divided into a mid-term phase, which ranges from 100 m to 2500 m of sliding distance, and a long term-phase, which covers the sliding distance after 2500 m. The wear rates of the lower disks are always superior to the wear rates of the upper disks. The wear of the disks depends on different factors, for example: temperature, surrounding phases, sliding velocity, mechanical strain, surface roughness, coating thickness and hardness, deposition of debris. Most of these parameters are the same for the lower and the upper disks or vary in negligible way, however, due to its increased angular velocity, the lower disks run at higher absolute tangential velocity and cover a greater sliding distance. Therefore their surfaces are worn more compared to the ones of the upper disk.

The WC-Co coatings show slightly reduced wear rates in the run-in and mid-term phases, probably the higher binder content and the consequent lower microhardness properties allow

increased resistance to wear. Another reason might be related to the presence of cracks in the coatings (figure 4) which can favour the inclusion of debris or a prevalence of adhesive wear with respect to the abrasive one. At any rate the differences are very small and in the long term phase are not significant.

Abrasive and adhesive wear occurred simultaneously, however the smoothing of the surface might favour an increasing importance of adhesive wear. After the run-in phase the adhesive wear might be dominant concerning the metal matrix, while the carbides are worn by abrasion and the adhesive wear of the matrix seems to precede the abrasive wear of the carbide.

All the coatings shown very high wear resistance during the last 4000 m of sliding, where the wear rates of the standard and non-standards parameters coatings were almost the same. In this phase adhesive wear dominates the abrasive wear, in fact the smoother the surface becomes, the higher is the influence of the adhesive wear.

All wear test pieces were simultaneously exposed to two different strains: the sliding friction and a dynamic change of the load. Some disks, which all were coated with the WC-Co powder by non standard parameters, failed due to fatigue wear. The coating chipped off as a whole, this might be caused by the high tensile stresses: the load pushed the coating to the interfaces when it was applied. In the time, when the surface was not exposed to the load, the interface of the bulk material and the coating returned to their initial state. This back and forth movement of the coating, together with the decreased adhesion strength and the elevated residual stresses, caused microcracks with the interface, which were likely to grow, because the adhesion of the coating is poor. The crack grew within the interface, until it reached the outer border of the coating and the cracks, which already were within the original coating. Finally, a portion of coating chipped off.

The adhesion is related to the summation of the intermolecular interactions between two materials, while cohesion refers to the sum of the intermolecular interactions within one material. The bonding forces between the surface and the substrate and between the different coatings layers are mainly physical, even if the solubility of the contact materials has an influence on adhesion and cohesion. The failure of the bonding agent, in the case of the WC-Co/1 coatings, was caused probably by non perfect contact with the whole surface of the frontal part of specimens, due to production inaccuracies. This has the effect to reduce the surface area of contact, moreover, in addition to the normal force, the bonding agent and the test specimens are exposed to a couple of forces, leading to a torque, which causes tangential strain and consequent lower resistance of glue. This failure hindered the evaluation of the adhesion or cohesion forces for the WC-Co coatings sprayed with standard parameters, even if the obtained values are in the range of the cohesion strength measured on the WC-CoCr coatings. On the other side, the WC-Co coatings, sprayed with non standard parameters, showed insufficient adhesion to substrate and broken at the substrate-coating interface at considerably low loads. The decrease of adhesion is an indication for a worse attaching of the coating, probably due to the lower amount of oxygen in the combustion gas, with consequent a reduction of particles velocity. Also elevated tensile stresses, which are caused by the higher particle temperature, could contribute to the decrease of the adhesion: the residual stresses might lead to a reduction of the contact area due to microcracks within the interface.

When the WC-CoCr powders are sprayed, the bonding properties of the substrate-coating system increases and consequently the adhesion of these coatings is superior to the one of the WC-Co coatings. The adhesion was stronger than the cohesion and the failure was found within the coating layer, with higher strength values when spraying adopting standard parameters. This might be caused by the chromium containing matrix, which might tend to form a stronger contact with the substrate surface. The lower cohesion of non-standard parameters coating might be mainly caused by increased porosity: due to the lower velocity of the spraying particles, they do not form such a compact layer as with standard parameters.

The microstructure features of layers and the presence of cracks in the WC-Co coatings proof the high tenacity of coatings, in fact even if cracked the WC-Co coatings never losses broken parts.

5. Conclusions

The properties of the surface of a component greatly influence its performance and lifetime, among the numerous and different surface treatments useful to improve the properties of a surface, thermal spray processes gained great interest and allow many advantages, being able to produce large assortment of wear and corrosion resistant protective layers. From this point of view, thermal spray processes may be useful tools to increase surface properties of PM parts, without compromising their toughness characteristics. Moreover, the presence of porosity may constitute an optimal base, providing adhesion between substrate and applied coating, without the requirement of additional operations, like grit blasting, to roughen the substrate surface.

In this paper, the properties of unalloyed and Ni, Cu and Mo or only Mo alloyed sintered steels, coated by thermal spray using the HVOF process, has been studied. Two different WC based powders, WC-Co and WC-CoCr, have been applied with two set of process parameters: neutral atmosphere, it means standard parameters, and reducing atmosphere, with a lower oxygen content.

The substrate composition does not remarkably influence the properties of the coating layers and the adhesion between the substrate and the layer, the main influences being related to the powders composition and spraying parameters.

The two powders, WC-Co and WC-CoCr, shown in the as-sprayed state decomposition of the tungsten carbide and an amorphous metal binder. The WC-Co coatings contain more tungsten oxidation products compared to WC-CoCr coatings. When using the non-standard parameters the WC decomposition decreases and the amount of decrease is much lower if WC-CoCr powder is sprayed. Chromium might have a function as an oxidation buffer: in oxygenating atmospheres it partly protects tungsten carbide from oxidation by forming Cr₂O₃, whereas this reaction is partly suppressed in reducing atmospheres, so that the amount of WC-oxidation products does not change much.

Changing the spraying parameters from standard to non-standard, also affects the micro-hardness of the obtained coatings, due to the lower velocity of the sprayed particles what leads to a higher porosity, it decreases.

The wear mechanisms, which occurred during sliding friction, are similar for the different coatings: after a run-in phase, in which the asperities are mainly abrasively worn away, adhesive and abrasive processes take place. The superior long-term wear resistance of the WC-CoCr coating is not influenced by the change of the spraying parameters: the chromium containing metal matrix seems to compensate the elevated roughness and the increased tensile stresses through its toughness and its carbide binding property.

Adhesion of the coatings was the weak point of coatings originated from the WC-Co powder, whereas the cohesion was sometimes insufficient within the WC-CoCr coatings. The non-standard parameters WC-Co coatings did not adhere to the different alloy substrate, changing the standard parameters in the performed way, weakens the substrate coating system by reducing the adhesion, by increasing porosity and by causing elevated residual stresses. Some of WC-Co non standard parameters coatings failed because of fatigue wear within the sliding distance due to bad adhesion. Chromium seems to increase the carbide binding function of the metal matrix and to reduce the residual stresses within the coating.

In summary of the previous stated, it may be said, that the overall performance of the WC-CoCr coatings, which was sprayed with standard parameters, is the best, the supreme quality of WC-CoCr coatings being the reduced tensile stresses and the good bonding strength. All these properties relate to the presence of Cr within the metal matrix, it partly prevents WC from oxidation, it increases the the hardness via solid solution hardening and by forming Cr₂O₃, what also increases the corrosion resistance of the coating, and it binds tungsten carbide in an excellent way.

References

- [1] D.G. Rickerby, M. Matthews, *Advanced Surface Coatings, Handbook of Surface Engineering*, McGraw-Hill, New York (1991) 1-13.
- [2] M. Rosso, "The excellence of PM tool steels, their modern competitiveness, reliability and innovation", Proc. of the 7th Int. Tooling Conference, TOOL06, Torino, Italy, May 2006, Vol II, 389-400.
- [3] R.C. Tucker, *Thermal spray coatings*, Vol. 18, ASM Handbook, ASM International, 1993, 497.
- [4] H.E. Boyer, *Metals Handbook Vol. 7* (1984) 451.
- [5] H.A. Ferguson, *ASM Handbook Vol. 4*, ASM International, (1991) 229.
- [6] P. Novak, J. Serak, D. Vojtech, "Effect of Plasma nitriding conditions on abrasive wear behavior of Nb-containing PM tool steel", Proc. of DFPM2005 Int. Conf., Stara Lesna, Slovakia, September 2005, 239-245 .
- [7] M. Rosso, M. Actis Grande, "Influence of different thermal treatments on wear resistance and mechanical properties of Astaloy CrM and Distaloy AB", Proc. of the DFPM2002 Int. Conf., Stara Lesna, Slovakia, September 2002, 278-283.
- [8] M. Rosso, M. Actis Grande, E. Romano, "High pressure die casting: improvement of tool life by thermal sprayed coatings", Proceedings of the 10th Jubilee Int. Sci. Conf. on Achievements in Mechanical and Materials Engineering, Gliwice, Poland, 2001, 505-509.
- [9] M. Rosso, M. Actis Grande, D. Ugues, "Properties and erosion resistance of HVOF deposited coatings",

- Proceedings of EUROPM 2001, Acropolis Convention Centre, Nice, France, Vol. IV, 2001, 339-344.
- [10] D. Ugues, M. Actis Grande, M. Rosso, E. Rastelli, "Trattamenti termici e rivestimenti di acciai per utensili : potenzialità innovative" Proceedings of 19° Convegno Nazionale Trattamenti Termici, 20-22 Maggio 2003, Salsomaggiore Terme, Italy, Editor AIM, Cd-Rom.
- [11] M. Rosso, M. Actis Grande, D. Ugues, "Optimisation of Thermal Spray Coatings based on Composite Materials", Proceedings of the 16th Int. Plansee Seminar 2005, Powder Metallurgical High Performance Materials, PLANSEE Holding AG, Reutte, Tyrol, Austria, 31st May – June 3rd, 2005, Vol 1, 412-421.
- [12] M. Lucaci, R.L. Orban, M. Rosso, M. Actis Grande, "NiAl coatings on steel substrates by plasma spray depositing", Proceedings of RoPM 2005, Third Int. Conf. on Powder Metallurgy, 7-9 July 2005, Sinaia, Romania, vol. 1, 473-478.
- [13] M. Rosso, M. Actis Grande, D. Ugues, "Study of coatings to be applied on metal appliances for the picking up of agricultural products", Proceedings of the 13th Int. Sc. Conf. "Achievements in Mechanical & Materials Engineering", May 16-19, 2005, Gliwice-Wisla, Poland, 2005, 551-554.
- [14] M. Rosso, "La deposizione di film spessi con processi thermal spray", Manuale di Trattamenti e Finiture, TECNICHE NUOVE, Ottobre 2003.
- [15] D. Ugues, M. Actis Grande, M. Rosso, "Riporti HVOF per il miglioramento della resistenza a erosione di componenti destinati ad impianti trattamento acque" La Metallurgia Italiana 7 (2004) 57-61.